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SOFT GAMMA RAYS FROM BLACK HOLES VERSUS NEUTRON STARS

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ABSTRACT

The recent launches of GRANAT and GRO provide unprecedented opportunities to study compact collapsed objects from their hard x-ray and gamma ray emissions. The spectral range above 100 keV can now be explored with much higher sensitivity and time resolution than before. Here we review the soft gamma ray spectral data of black holes and neutron stars, radiation and particle energization mechanisms and potentially distinguishing gamma ray signatures. These may include soft x-ray excesses versus deficiencies, thermal versus nonthermal processes, transient gamma ray bumps versus power law tails, lines and periodicities. We also outline some of the highest priority future observations that will shed much light on such systems.

I. INTRODUCTION

Gamma ray observations of compact objects likely provide the most penetrating probe and diagnostics of neutron star and black hole systems. The recent launches of GRANAT and GRO provide new opportunities to study these objects above 100 keV with unprecedented spatial and time resolutions. In particular, gamma ray observations hold the promise of being able to distinguish between black holes and neutron stars based on their spectral and temporal behaviors. In this paper we will review the current status of observational data, radiation and particle energization mechanisms, astrophysical models for soft gamma ray emission, and summarize the potential distinguishing signatures of neutron stars and black holes. For the present discussions we will define soft gamma rays as the spectral range from ~100 keV to ~100 MeV.

Recent observations suggest that the most prominent soft gamma ray sources in the sky fall into 4 main categories: a) Galactic black hole candidates including both steady x-ray sources such as Cyg X-1 and transient sources (x-ray novae) such as A0620, GS2000+25, novae Muscae etc; b) AGN sources; c) young pulsars such as Crab and Vela and d) gamma ray bursters. The power per decade spectra (νF_ν) of these sources are sketched in Fig. 1. It is widely believed that the former two groups are associated with black holes while the latter two groups are associated with neutron stars. Another popular view is that black holes are thermal gamma ray sources while neutron stars are nonthermal gamma ray sources. However, the persistent power law gamma ray tails observed in many AGN sources suggest that if they are indeed black holes, then either black hole can also emit nonthermally, or the power laws are produced elsewhere such as in a jet rather than in the accretion disk itself. Since both pulsars and gamma ray bursters are popularly associated with isolated, non accreting neutron stars (see e.g. Liang and Petrosian 1986 for review), some authors also believe that accreting neutron stars (e.g. x-ray pulsars, x-ray bursters, LMXBs etc) cannot be strong soft gamma ray emitters (Sunyaev et al 1991). However recent detection of gamma rays from an increasing number of accreting neutron stars: GX1+4 (X-ray pulsar), GX354+0 (x-ray burster) etc casts such segregational themes in doubt. Only systematic long term observations leading to much broader databases can clarify such issues.

We first review the spectral data in Section II. In Section III we briefly list the radiative and particle energization processes relevant to soft gamma ray emission. In Section IV we discuss astrophysical models of black hole and neutron star gamma ray

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sources. Section V is devoted to speculative potentially distinguishing signatures of black holes and neutron stars.

II. REVIEW OF SPECTRAL DATA

Figure 2 gives some sample spectra of black hole candidates while Figure 3 gives sample spectra of pulsars and gamma ray bursters. A characteristic of nonthermal neutron star emission is a persistent power law tail of index 2 - 2.5 extending out to > 10 MeV with possible low energy turnover (x-ray deficiency) in the case of Vela pulsar and gamma ray bursters. On the other hand black hole candidates seem to show strong variability both at the soft x-rays below 10 keV as well as gamma rays above a few hundred keV. During the quiescent state the spectrum is a power law of index 1.5-2 from ~ kev to ~ hundreds of keV followed by an exponential cutoff suggestive of thermal emission. During the gamma ray high state of Cyg X-1(Ling et al 1987), 1E1740.7-2942 (Paul et al 1991) and the Briggs source (Briggs 1991), the continuum exhibits a bump at 400 keV - 2 MeV with a sharp cutoff at high energies, again suggestive of thermal origins.

Spectra of x-ray novae evolve with time (Fig. 2), with the early phase resembling the soft x-ray high state of Cyg X-1 or GX339-4, and the late time spectra resembling the quiescent (low) state of Cyg X-1. It is this similarity in spectral behavior and the high orbital mass of A0620, the prototype of this class of transient sources, that prompt most authors to associate x-ray novae with black hole candidates (Sunyaev et al 1991). Crab and Vela represent the prototype of nonthermal gamma ray sources driven by strong fields. The low energy cutoff appears a measure of their age. It is interesting that the typical GRB spectrum falls in between the Crab and Vela.

AGN spectra (e.g. Cen A, NGC4151) seem to contain signatures of both Galactic black hole candidates as well as those of neutron stars. In the low gamma ray state (Fig.4) the spectrum is typically a power law with exponential cutoff at a few hundred keV - MeV, similar to Galactic black hole candidates in their quiescent state. But in the high gamma ray state (Fig.4) it often has a nonthermal power law tail extending out to very high energy. It is possible that this nonthermal power law comes from a separate component, e.g. a jet, rather than the black hole accretion disk itself.

III. RADIATION AND PARTICLE ENERGIZATION PROCESSES

Table 1 summarizes the most important continuum radiation processes in the gamma ray regime. We note that inverse Compton is the most popular mechanism for quiescent black hole emission (e.g. Sunyaev and Trumper 1979) while pair-dominated emission might be relevant to their gamma ray high states (Liang and Dermer 1988). Figure 5 illustrates the two regimes in the B versus (n, n_γ) plane where n is particle density and n is photon density. In the low density high field regime, nonthermal synchrotron, curvature, resonant Compton and 1-photon pair processes dominate. In the opposite regime, thermal bremsstrahlung, Compton and two-photon pair processes dominate. It is likely that the former regime is relevant to high-field neutron star emission while the latter regime is relevant to black hole candidates.

It is known from early days of accretion disk theory (Thorne and Price 1975) that the only way a black hole accretion disk can become hot enough to radiate hard x-rays is to become optically thin. Moreover, how hot an optically thin disk gets depends on i) how many soft photons, both internal and external, are cooling the system (Shapiro et al 1976) and ii) how efficient is the coupling between the ions which form the heat reservoir and the electrons and pairs which are the cooling agents. The question of the abundance of soft photons will be addressed in the next section.

For a plasma to remain thermal, i.e. Maxwellian, the thermalization (or randomization) time must be shorter than the cooling time due to radiative processes. Such thermalization time is usually associated with the Coulomb coupling time between ions and electrons, which imply a high particle density. At very low density so that the plasma is collisionless, under special conditions thermalization may be achieved via collective processes on plasma oscillation time scales (e.g Max 1982, Begelman and Chiueh 1988). However, even at high particle density there is a limit to the maximum electron temperature of a Coulomb plasma (Dermer 1989). Since the ion virial temperature cannot exceed ~ 100 MeV around a nonrotating black hole, electron temperature is estimated not to exceed ~ 3.5 MeV via Coulomb heating by the ions. So thermal plasmas around black holes cannot produce many gamma rays above ~ 10 MeV.

Table 1. Radiation Processes

A. Optically Thin Limit:
- lepton-lepton: bremsstrahlung, 2-γ pair annihilation
- lepton-ion: bremsstrahlung
- lepton-photon: Compton, double Compton, resonant scattering
- lepton-B: synchrotron, curvature, 1-γ pair annihilation
- photon-photon: 2-γ pair production
- photon-B: 1-γ pair production
- ion-ion, ion-photon: π_0 decay

B. Optically Thick Limit:
- $\tau_{absorb} >> \tau_{sc} > 1$: true blackbody
- $\tau_{sc} >> \tau_{absorb} > 1$: modified blackbody
- $\tau_{sc} >> 1 > \tau_{absorb}$: Wien
- $\tau_{\gamma\gamma}, \tau_{sc} > 1 > \tau_{absorb}$, and ℓ(dimensionless compactness) > 1: pair-dominated spectrum

For nonthermal processes, whether it is operating around a black hole or neutron star, we should distinguish between thick target and thin target distributions. Table 2 summarizes the different particle acceleration mechanisms and relations between particle and photon indices.

Table 2. Nonthermal Processes

A. Direct Acceleration of Electrons and Problems
1. shocks & turbulence: difficult to get -2 power law, too slow
2. waves: hard to get in phase with particle
3. neutral line current sheets: act on too few particles
4. macroscopic $E_{//}$: easy to short out

B. Acceleration of Ions: less radiative loss
1. Ion couples to electrons via Coulomb or collective processes
2. Ion-Ion collisions: pion production and decay
3. Ion-Photon collisions: photon pion production

C. Relation between Power Law Indices : $f(\gamma) \propto \gamma^{\delta}$ ----> $N_\nu \propto \nu^{-n}$
1. thin target (steady distribution): $t_{accel} << t_{cool}$: $n=(\delta+1)/2$
2. thick target (cooling distribution): $t_{accel} >> t_{cool}$: $n=(\delta/2)+1$

IV. ASTROPHYSICAL MODELS

How do compact objects emit gamma rays? We will first consider thermal scenarios for accreting black holes and nonthermal scenarios for nonaccreting neutron stars. But we will also speculate on alternative scenarios.

A. Thermal Models for Black Holes:

Within the context of thermal accreting disks around black holes, it has been suggested that there are at least 3 phases with increasing temperature (Fig.6, Wandel and Liang 1991):

a) optically thick, physically thin disks emitting blackbody radiation of UV to soft X-ray temperatures (Shakura and Sunyaev 1973); b) disks with optically thin inner region cooled by inverse Comptonization of soft photons (external or synchrotron,Thorne and Price 1975, Shapiro et al 1976); c) disks where the soft photon source is completely quenched in the inner optically thin region; such regions can only cool inefficiently via bremsstrahlung and could heat up to relativistic temperatures, leading to copious production of e+e- pairs and possibly the dominance of the pairs (Svensson 1984, Zdziarski 1984, White and Lightman 1989, Kusunose and Takahara 1988). The pair-balance emission of such regions give rise to a bump in the 400 keV - ~ MeV region (Ramaty and Meszaros 1981, Liang and Dermer 1988). The escape of some of the pairs to annihilate in the cool circumstellar or interstellar medium will likely lead to correlated appearance of a narrow 511 keV line (Lingenfelter and Ramaty 1989, Dermer and Liang 1989).

Once we accept this kind of scenario for gamma ray emission from black holes, then a number of consequences can be predicted that can be confronted with observational data. For a nonrotating hole we expect that: i) the fluence of the narrow 511 keV line, coming out of escaped pairs from the gamma ray emitting source in this picture, should be correlated with the fluence of the gamma ray bump and its value can be computed dependent on the geometry of the disk model (Dermer and Liang 1989); ii) the mass of the black hole can be constrained as a function of the disk Keplerianess parameter from the gamma ray bump color temperature and the ratio of gamma ray flux to total (x-ray plus gamma ray) flux (Liang 1990); iii) the gamma ray bump should be correlated with pion decay continuum emission below ~ 70 MeV whose intensity can be calculated (Dermer 1989); iv) a globally average viscosity parameter can be estimated for the pair cloud as a whole (Liang 1991); v) upper limit on the magnetic field of the emission region can be obtained from the hardness of the gamma ray spectrum via the lack of synchrotron soft x-rays (Dermer and Liang 1989). In particular, ii) can be used to check the overall self-consistency of the pair cloud black hole accretion model when we have multiple data points for a single object, i.e. many episodes of gamma ray flaring in which both the x-ray and gamma ray spectra are obtained.

B. Nonthermal Models for Neutron Stars:

Conventional ideas of nonthermal gamma ray emission from isolated neutron stars center around the acceleration of electrons and pairs by macroscopic electric fields parallel to magnetic fields. The hardness of the power law (photon index ~ 2) and the rapid time scales (down to ms) make it difficult, if not unlikely, for acceleration by shocks, waves and turbulences. In both young radio pulsars and gamma ray bursters (if they are indeed associated with strong field neutron stars), it is yet unclear if the emission is from near the surface or the outer magnetosphere (Fig. 7). If it is surface emission then the gamma rays must be strongly beamed. The origin of the accelerator in the pulsar case is of course stellar spin ($\mathbf{V}$ x B), but the origin in the gamma ray burst case is far from clear. But the similarity of the GRB spectra to pulsar spectra is striking, with most spectral shapes lying between Crab and Vela. In fact, in many bursts the spectrum starts out hard with a total lack of x-rays similar to the Vela spectrum and evolves towards more x-rays at late times similar to Crab.

Even though we still have no satisfactory model of gamma ray emission from GRBs, it is likely that the emission will involve a combination of synchrotron and curvature radiation and resonant Compton scattering together with some form of pair cascade, similar to pulsars. In the model of Ruderman and Cheng (1988) for young pulsars, they predict a limiting luminosity of ~ 5×10^{36} erg/s (Fig. 8). Note that this is considerably below that observed for typical black hole candidates (10^{37-38} erg/s). This may be used as a discriminant between pulsar and black hole gamma ray sources.

C. Alternative Scenarios:

What about nonthermal black hole models and thermal neutron star gamma rays? Despite the popularity of thermal disk models for black holes there is no compelling

reason to exclude nonthermal models. In particular for rapidly rotating black holes which can sustain a macroscopic ordered B-field nonthermal accelerations seems likely (e.g. Begelman et al 198). Even for nonrotating holes the shearing motion can in principle also lead to equipartition fields up to 10^{6-7}G whose reconnection can provide plenty of free energy for particle acceleration (Galeev et al 1979). However, such fields will also unavoidably lead to copious production of soft synchrotron photons which will cool the plasma, making it hard to pump most energy into gamma rays.

Similarly, accreting neutron stars will have an abundance of soft photons, both from blackbody emission from its surface and synchrotron soft photons from the inner magnetosphere. Hence it might be difficult to sustain a hot thermal pair cloud near the star emitting gamma ray bumps or even nonthermal accelerators. It has therefore been a popular belief (e.g. Sunyaev et al 1991) that accreting neutron stars cannot be strong gamma ray emitters above ~ 100 keV. However, recent results on GX1+4 (Fontera et al 1989, Sunyaev et al 1991) and GX354+0 (Cook et al 1991) as well as the possible association of a source in Terzian 2 (Barret et al 1991) with an x-ray burster, plus the possibility that Cyg X-3 (Meegan et al 1979) is an accreting neutron star all suggest that accreting neutron stars may be occasional strong emitter of soft gamma rays.

Recent works by the Columbia group (Kluzniak et al 1988, Cheng and Ruderman 1991) suggest that the disk-neutron star magnetospheric boundary may be the site of an efficient accelerator leading to emission of gamma rays. However, the soft x-rays will remain a problem for any such model. Also in the case of GX1+4 the gamma ray luminosity can become a good fraction of Eddington luminosity, making it unlikely that the gamma ray emitting region can be too far from the star due to energetic requirements.

D. Lines and Periodicities:

The presence of redshifted annihilation line and cyclotron lines in the 10's of keV had been considered telltale signs of neutron star emission, while narrow unredshifted 511 keV line (e.g. Leventhal et al 1989, Riegler et al 1985, Ling and Wheaton 1989) may be associated with black holes. However, recently discovered narrow gamma ray bumps from the 1E source and the Briggs source both may be peaking redward of 511 keV. If these are indeed black holes then the above discriminant may be in trouble. Moreover, if the B-field is weak enough so that the cyclotron line shifts into the few keV range then it can no longer be distinguished from, say Fe K lines or edges, which are observed from black hole candidates (Ebisawa 1991). However, if more than one well-defined harmonic (e.g. Ginga GRBs, Murikami et al 1988) is found then the case for neutron star is still strong.

Lack of (spin) period has always been a prerequisite for black hole candidacy. On the other hand, the case with QPOs is less clear cut. The fast QPOs (10's of ms period) is currently associated with neutron stars in most models (see e.g. Lamb 1990 for review), but the slow QPOs (~ few Hz) may well be associated with the accretion flow itself rather than the stellar spin, so it could arise in black hole systems as well as neutron star systems. Disk seismology is still in its infant stage and observations of QPOs in hard x-rays and gamma rays are still lacking.

V. POTENTIAL DISTINCTIONS

In Table 3 we list some of the gamma ray signatures currently associated with black holes and neutron stars. Whether they will stand up as universal signatures only time will tell. It is clear that spectrally, both black holes and neutron stars are capable of producing power law spectra in the mid-energy range from 10's of keV to few hundred keV. Their distinctions come in their variability in soft x-rays and gamma rays above a few hundred keV. Black hole candidates seem to have soft x-ray excesses at least episodically, whereas nonaccreting neutron stars often seem to have x-ray deficiencies. Black hole candidates

emit thermal gamma ray bumps episodically, whereas neutron stars have persistent power law spectra of photon index ~2. In addition to periodicity and QPOs, the distinction between black holes and neutron stars may also lie in the redshift and width of the annihilation line and its correlation with the continuum. Details of such distinctions remain to be worked out theoretically.

We believe the current observations with GRANAT and GRO will shed much light on the origin of gamma rays from both classes of systems. This work is partially supported by NASA NAG51515 and NAG51547.

Table 3. Potentially Observable Signatures of Black Holes versus Neutron Stars

	Black Holes	Neutron Stars
1. Continuum Shape in Quiescent State	1.5-2 power law with exponential cutoff above few hundred keV	2-2.5 power law with low energy flattening or turnover
2. Soft X-Rays	episodic excess with soft spectrum below 10 keV	x-ray deficiency, no excess
3. Gamma Rays	transient Bump at ~400 - 2000 keV	power law may vary, no bump
4. Periodicity	no fast period or QPO, may have slow QPO	period or QPO
5. Variability	long term transients	X and Gamma Ray Bursts
6. Lines	unredshifted 511 keV line Fe lines below 10 keV	redshifted 511 keV line cyclotron lines 10's of keV

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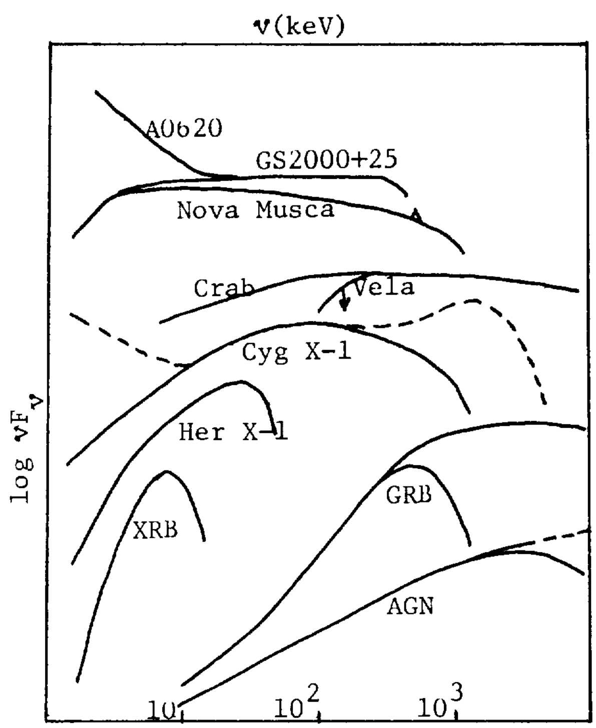

Fig.1 Power per decade spectra of 4 classes of soft gamma ray sources. For comparison we also sketch spectra of typical x-ray neutron star binaries. Vertical scale is arbitrary.

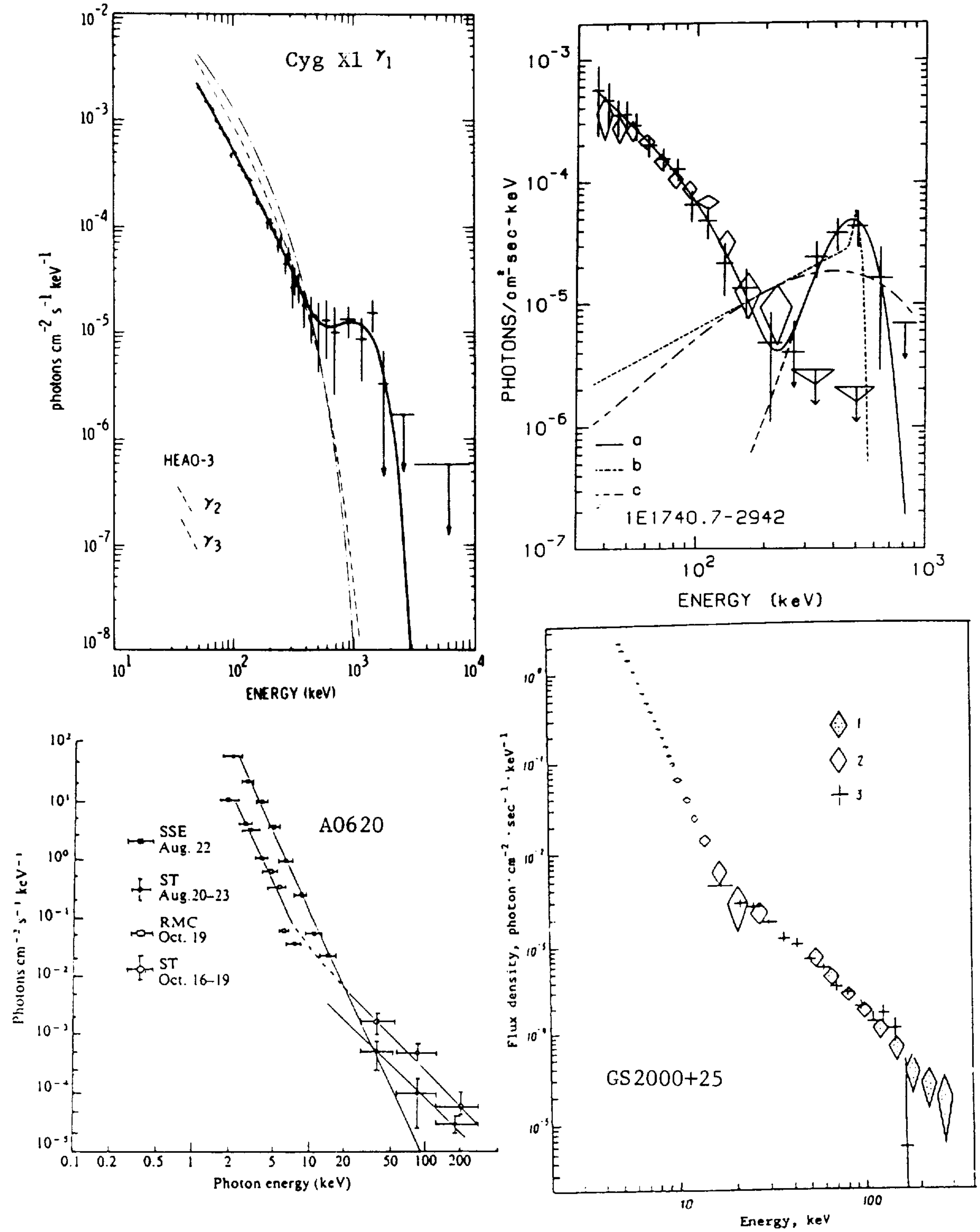

Fig. 2 Sample spectra of black hole candidates:Cyg X-1(Ling et al 1987), 1E (Paul et al 1991), A0620 (Coe et al 1976), GS2000+25 (Sunyaev et al 1988).

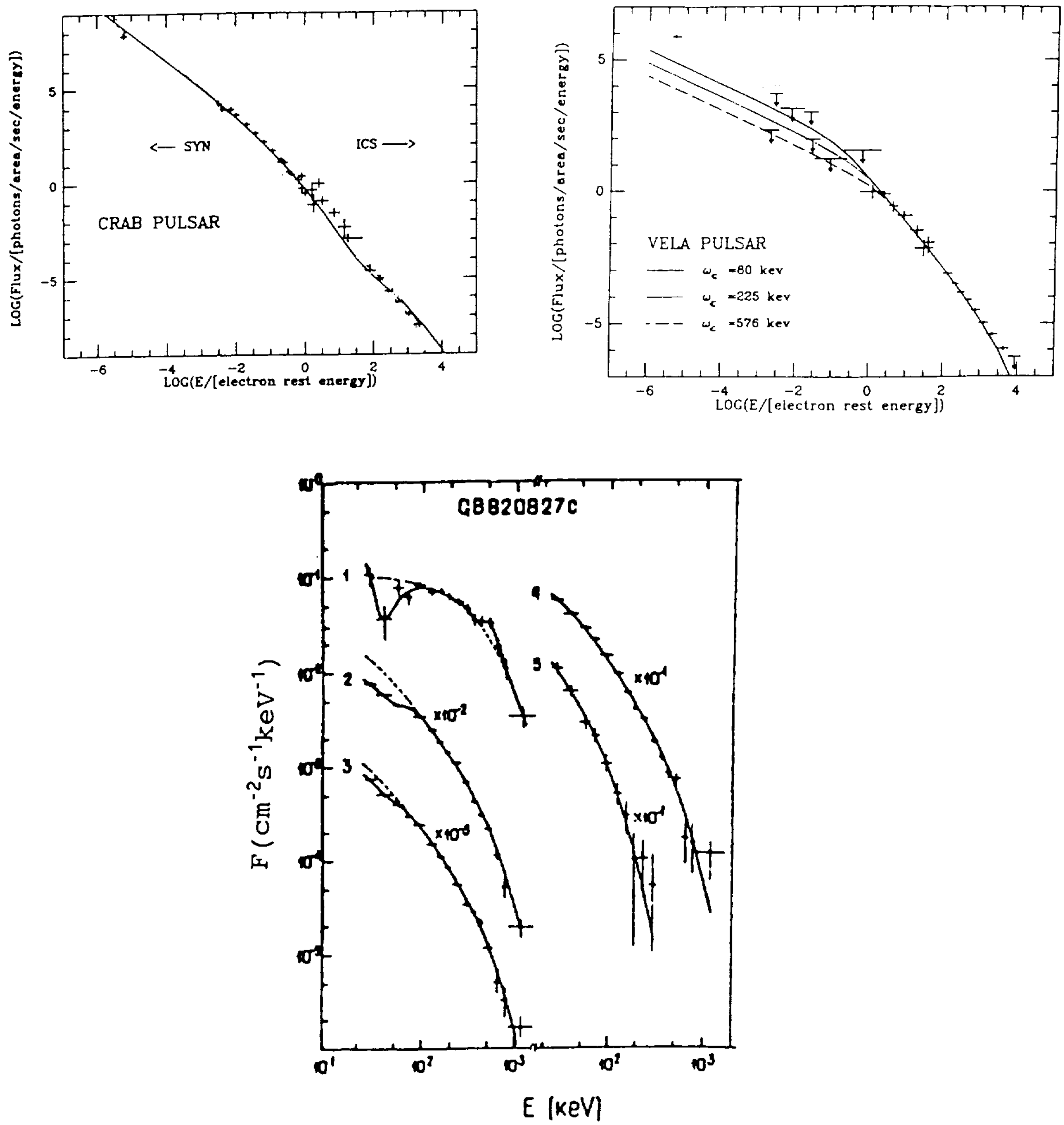

Fig. 3 Sample spectra of young pulsars and gamma ray bursters. Crab, Vela (from Cheng et al 1986), GB820827c (from Golenetskii et al 1984).

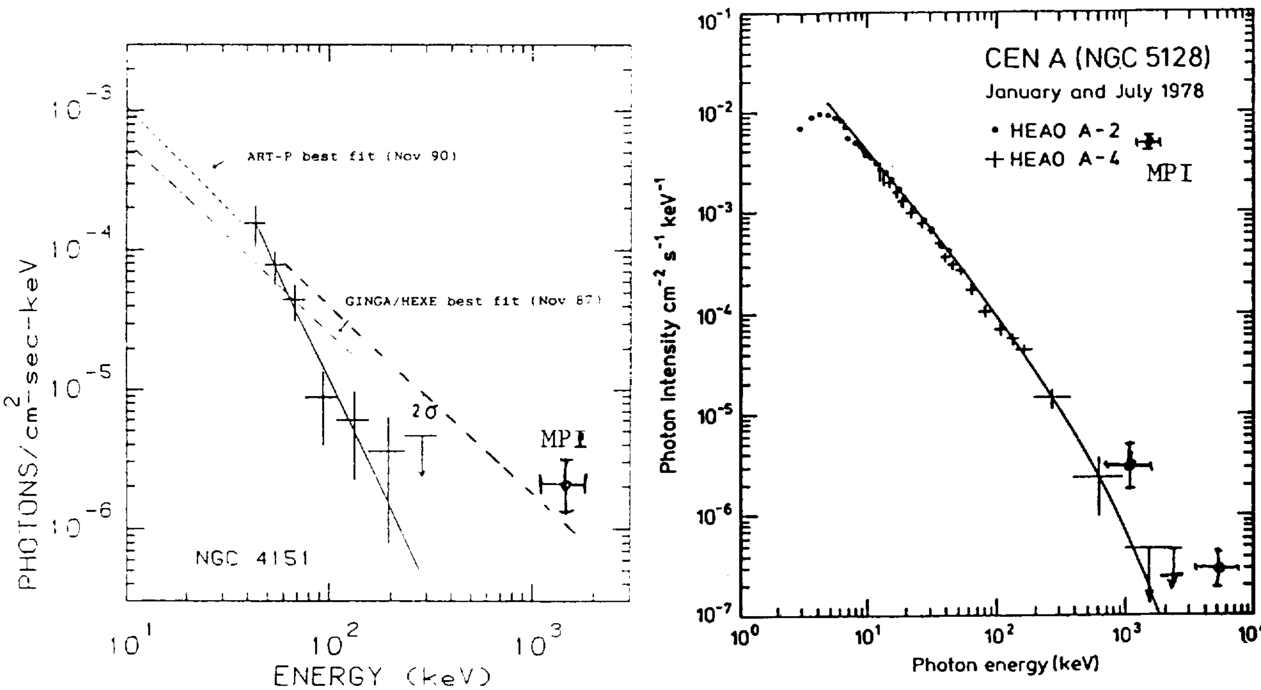

Fig. 4 Sample AGN spectra showing the variable high energy tails. NGC4151 (from Jourdain et al 1991), Cen A (from Baity et al 1981) adapted to include MPI data.

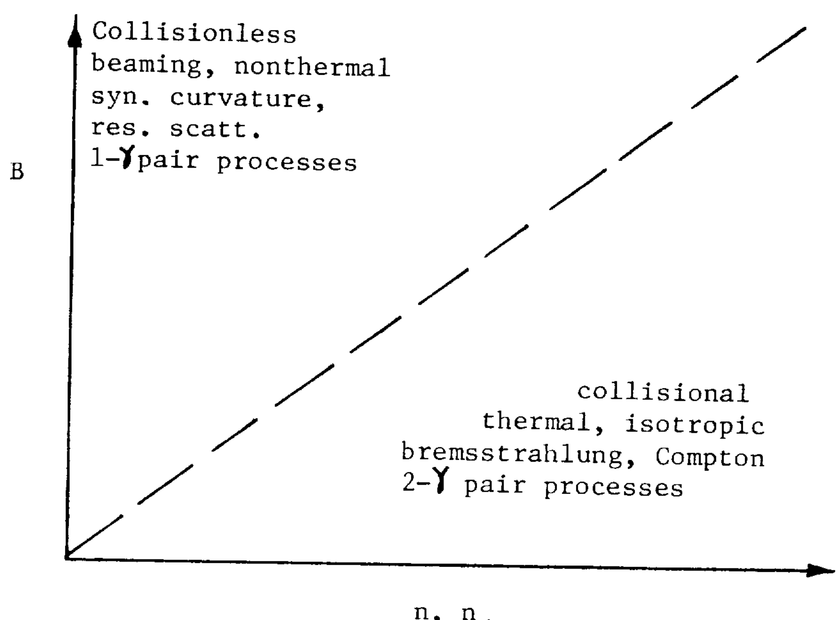

Fig. 5 Domains of B - n, n_γ plane showing the two regimes. The upper left is more relevant to neutron stars and the lower right is relevant to black holes.

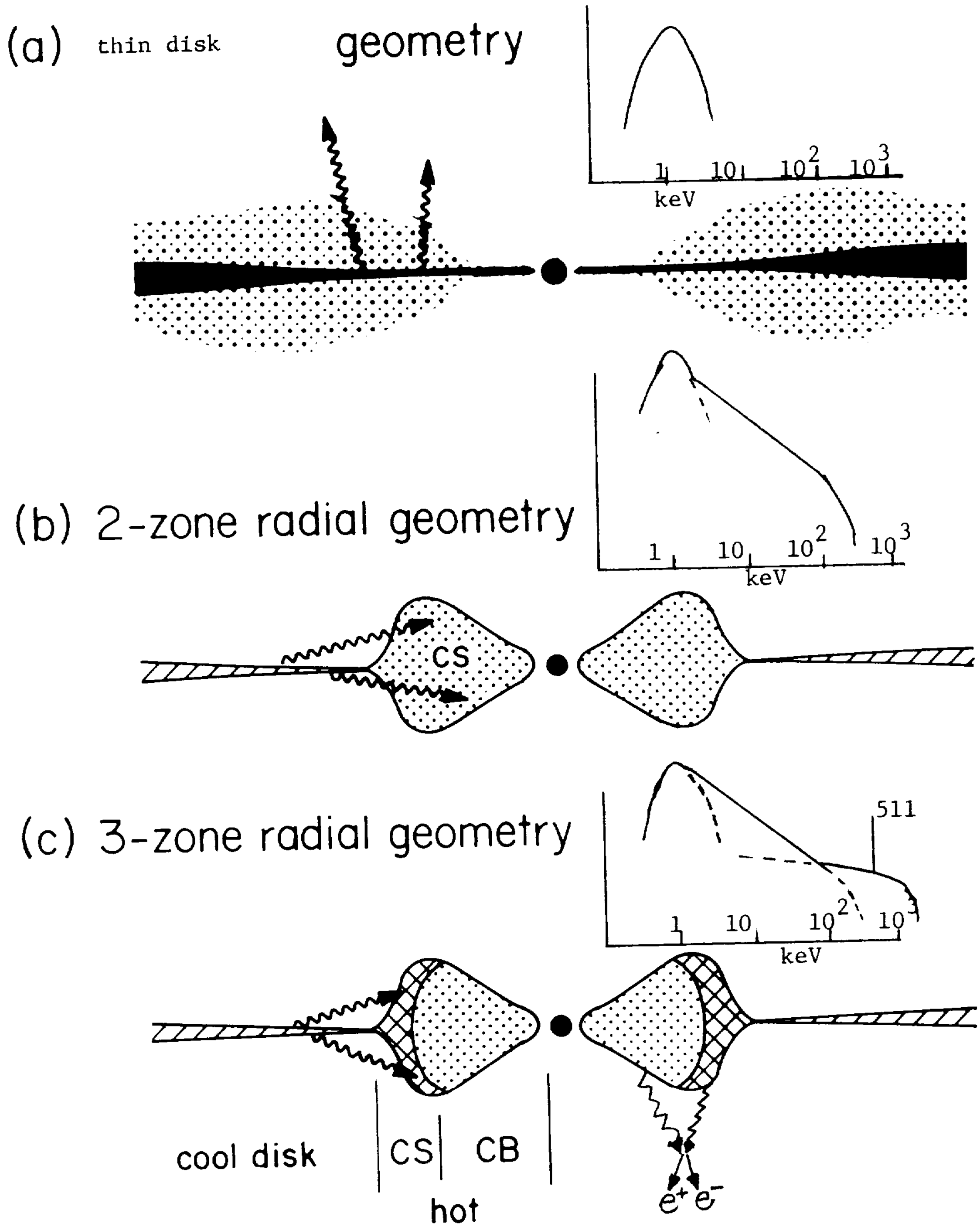

Fig. 6 Three phases of black hole accretion disks with their respective spectrum. CS= Comptonized Soft Photons. CB= Comptonized bremsstrahlung. Shaded area in (a) indicate a possible corona (adapted from Wandel and Liang 1991).

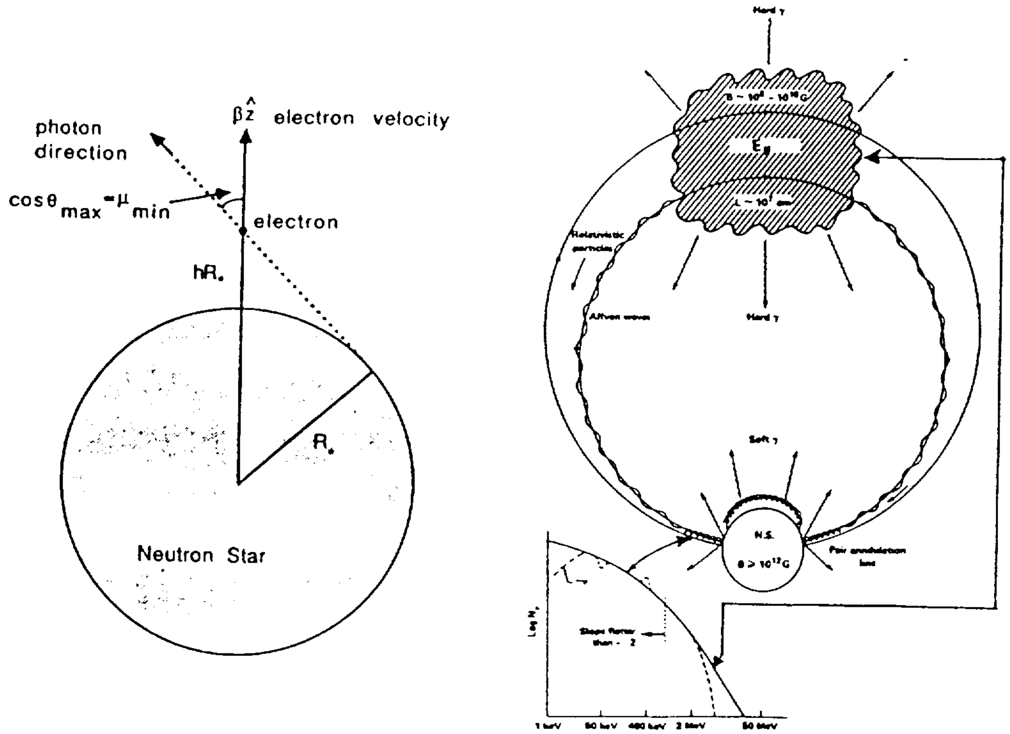

Fig. 7 Artist conception of two different scenarios of continuum spectra formation: (a) emissions by outwardly beamed electrons (pairs) near stellar surface (from Ho and Epstein 1989); (b) two component emission (from Liang 1989)

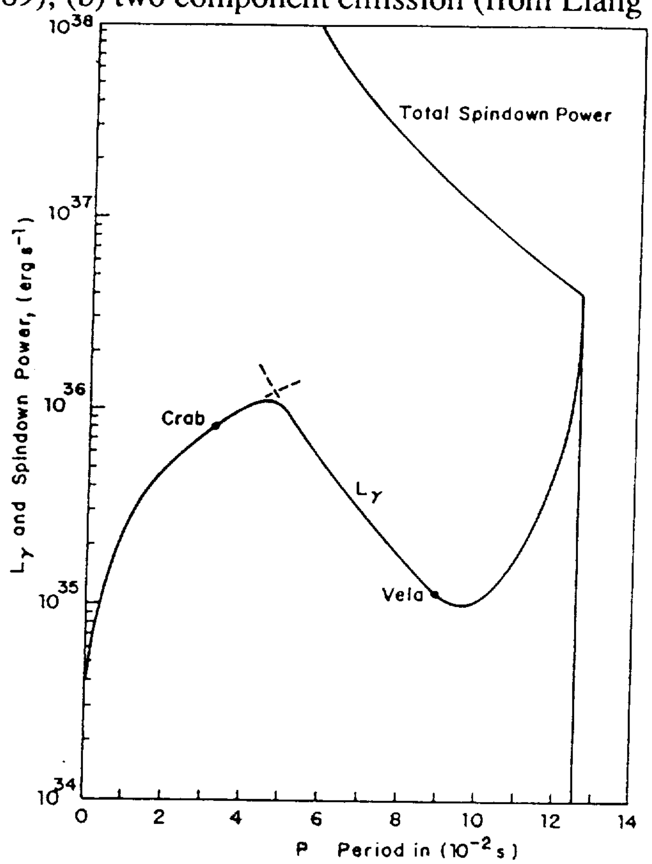

Fig. 8 Limit on gamma ray luminosity of pulsars based on the Ruderman and Cheng model (1988)